System Validation and Verification Testing for LISA

Preliminary Concepts

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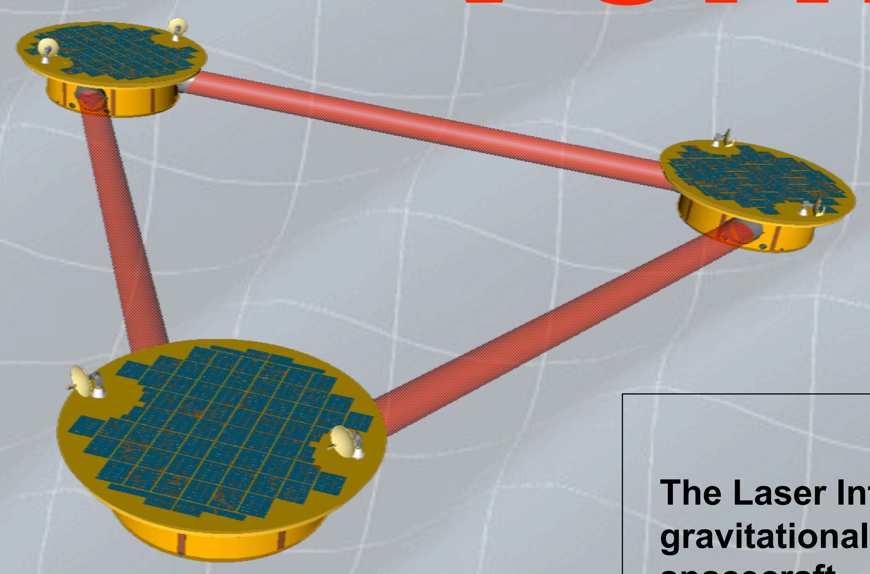
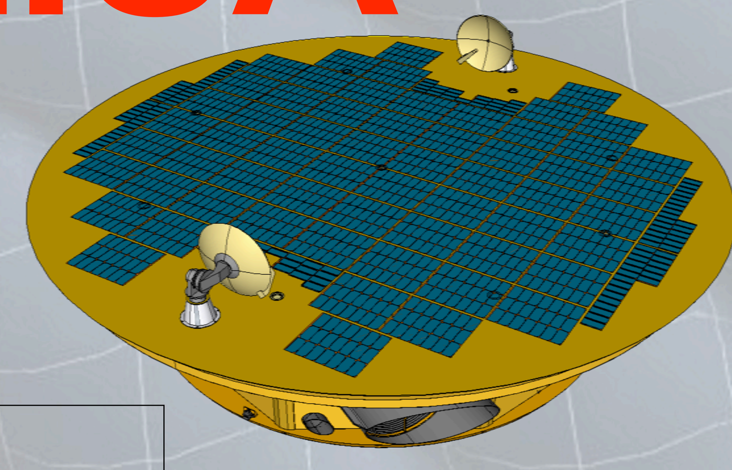




LISA Spacecraft

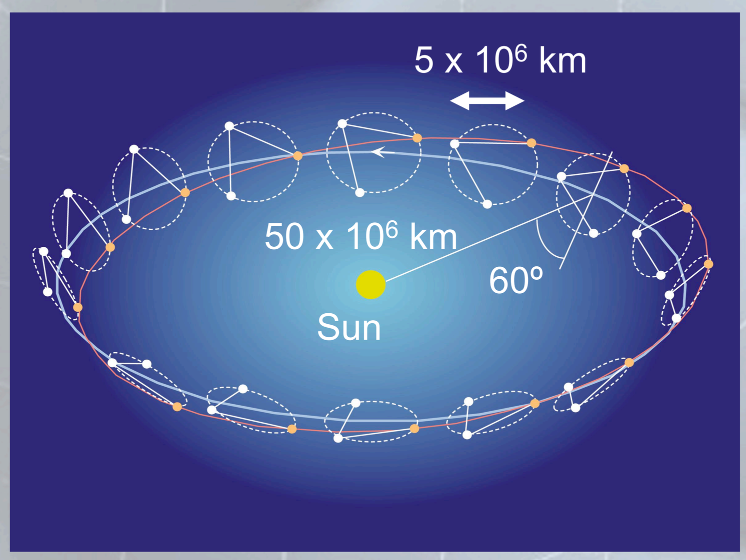
Abstract

The Laser Interferometry Space Antenna (LISA) mission is a set of 3 spacecraft that fly in a heliocentric orbit in an equilateral triangle formation to detect gravitational waves. Each side of the triangle is 5 million km long, and the formation detects passing waves by closely monitoring the distance between spacecraft.

The ideal for system-level testing of instruments and spacecraft is to "test as you fly". Given that the inter-spacecraft distance is approximately 13 times the distance between the earth and the moon, ground testing for the LISA instrument will not be able to meet this ideal in a number of areas, so a combination of testing, simulation, and analysis will be needed instead. This paper will outline some of the areas where direct testing on the ground will not be possible, and discuss some of ideas, concepts and methods to meet that challenge. The focus of the discussion will be on the optical and system-level aspects of the testing, as many of the issues associated with the proof masses and drag-free spacecraft are covered by the LISA Pathfinder mission.

Overview of the Mission

The LISA mission studies gravitational waves by detecting the strain they produce with a laser interferometer that measures the distance between pairs of freely floating proof masses arranged in a 5×10^6 km equilateral triangle constellation that orbits the sun 20º behind Earth's orbit. The plane of the triangle is angled at 60º with respect to the ecliptic. Each of the three spacecraft are in independent orbit around the sun, so no station-keeping is required to keep the constellation together. The proof masses are isolated from disturbances by using drag-free satellite technology that keeps a spacecraft centered around the proof mass as it moves.



LISA Orbit

Primary Testing Challenges

Most of the validation and verification testing for the LISA mission *IS* possible on the ground, but there are two major challenges for ground testing that will require atypical methods:

1) Testing a freely floating proof mass in a 1-g environment
2) Testing a very long arm interferometer without a long baseline

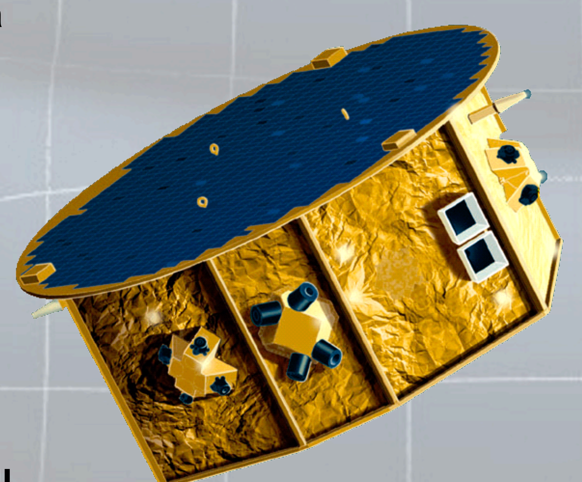
Free Flying Proof Masses

The requirement for a freely floating mass to serve as a proof mass for a gravitational wave detector is that it be free of residual forces to to a level of 3×10^{-15} m/s²/√Hz. In a 1-g environment this amounts to isolating the mass by a factor of ~ 10^{16} - a difficult task. Therefore ground testing to date has focused on developing a detailed noise model of some of the anticipated noise sources through testing of a torsion pendulum [Carbone, L., et al.; "Upper limits to surface force disturbances on LISA proof-masses and the possibility of observing galactic binaries", arxiv.org/abs/gr-qc/0611030]. The LISA Pathfinder mission is an additional opportunity to validate that we understand how to do ground testing that results in working flight hardware as well as reducing risk by testing the short arm interferometer (explained below).

In general, the Pathfinder mission will:

- validate the detailed noise model developed from torsion pendula
- validate the optical bench construction and testing techniques
- demonstrate six-degree of freedom operation near LISA required sensitivity

The Pathfinder mission is led by ESA and scheduled for launch in 2009. Currently all subsystems are undergoing CDR, with system-level CDR scheduled for June 2007. For more information see http://sci.esa.int/lisapf



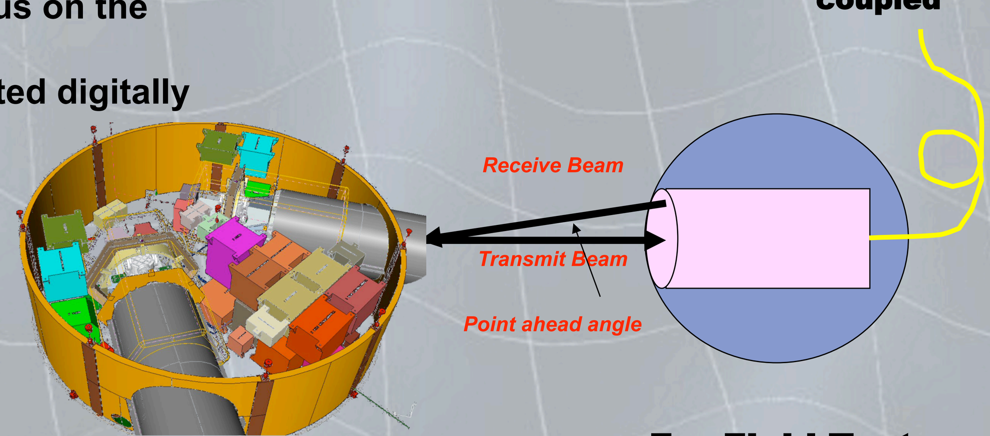
LISA Pathfinder Spacecraft

Long Arm Simulator

Although it is not physically possible to build a 5×10^6 km test bed on the ground, it is certainly possible to mimic some of the properties of such a test bed. One idea is to focus on the functional properties:

1) Delay: $\Delta t = d/c = 16.7$ sec one way, implemented digitally
2) Optical properties
   - Low received power (simple attenuation)
   - Spatial Power profile:
     - Transmit beam is gaussian
     - Receive beam is a "top hat"
   - Wavefront flatness
   - Polarization
   - Point-ahead angle
   - Pointing jitter
   - Secular variation in pointing due to orbits
3) Optical frequency spectrum
   - Carrier frequency - relative and absolute
   - Frequency noise
   - Clock noise transfer sidebands
   - Inter-spacecraft communications sidebands
   - Time-varying doppler shifts

Each of these properties is relatively easy to simulate with established laboratory techniques. It may not be necessary to simulate all of them simultaneously, simplifying the design.



LISA Spacecraft

Far Field Test Simulator

Full Constellation Testing

Constellation testing can be achieved using just one corner of the triangle for physical testing of one spacecraft at a time and using simulators for the rest. Below is a partial list of constellation functions that could be tested in such a set-up.

Just use this part

Top View of Vacuum chamber showing a possible LISA constellation testing layout

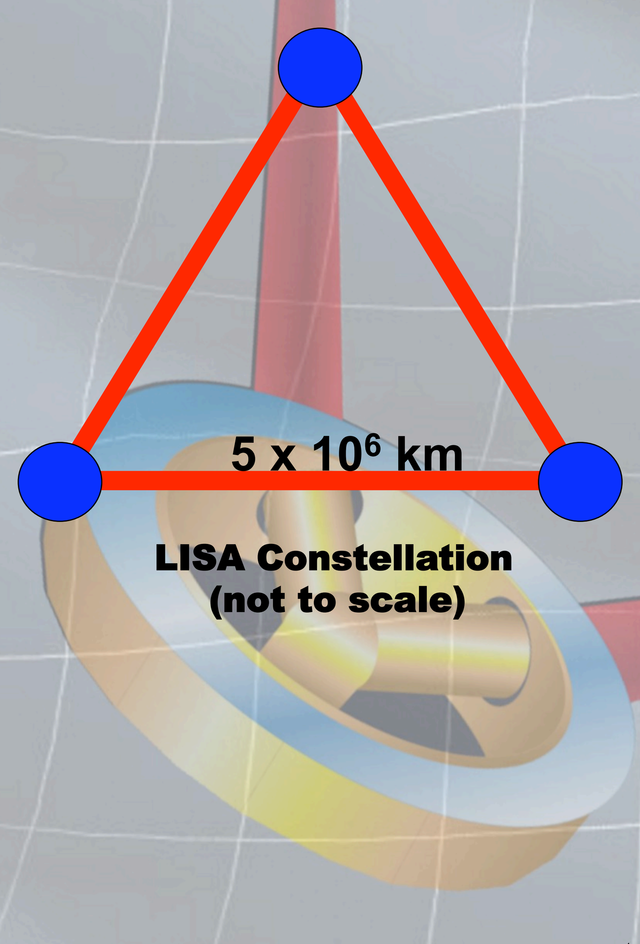
Constellation Function (partial list)	Brief Description
Constellation Management	Experiment control/coordination of various modes and transitions between modes.
Constellation processing and sampling	Collection and analysis of data of at least two kinds: 1) Housekeeping/sciencekeeping 2) Phasemeter (baseline is no on-board analysis)
Constellation performance validation	Monitoring and validating the performance of the constellation. Includes defining and checking/detecting the conditions necessary to transition into/out of a particular mode, such as science mode.
Constellation failure detection and recovery	Set of functions for conditions in which the constellation is only partially lost - such as loss of a single link. Includes transitions into possible safe modes, recovery scenarios, continuing operation, etc.
Acquisition - spatial	Establishment of the optical link between spacecraft. Proper pointing and orientation in space, as well as the exchange of optical power.
Acquisition - frequency	Establishment of laser frequency locking between spacecraft. Includes both pre-stabilization and arm-locking.
Frequency Management	Function for maintaining in-band beat notes on the photodetectors of each spacecraft.
Time Management	Time distribution among spacecraft.
Inter-spacecraft communications	exchange of data and control/command information between spacecraft.

Large Spacecraft Separation

The LISA arm length is 5×10^6 km, or about 400 times the diameter of the earth, or 13 x the distance from the earth to the moon. The nominal transmission loss is 100 dB, which means for every 1 Watt of transmitter power only 100 pW is received. If we were to use single mode optical fiber to simulate this same distance, the loss would be approximately 1 million dB.

Long Delay Simulation

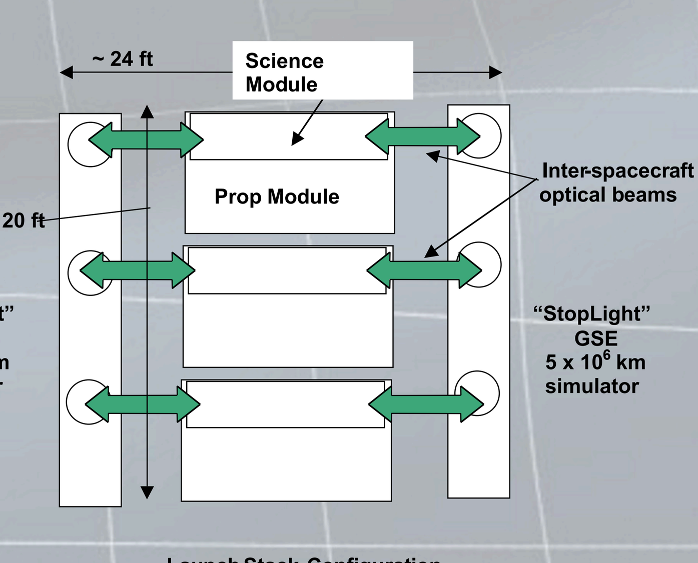
Instead of propagating the light (a delay) and then digitizing the phase, we can digitize the phase first and then delay the signal. Experiments at the University of Florida have already demonstrated proof of concept [Thorpe, J. I. PhD Thesis]



LISA Constellation (not to scale)

Launch Stack Testing

The LISA spacecraft are mounted in a vertical stack for launch, and may spend some time in that configuration waiting for launch or for other launch systems to be tested. A "stop light" configuration could allow at least simplified testing of the payload in the launch configuration, with communications over normal telemetry links. Simplified testing could include verifying at least low power transmitter operation as well as some alignment checks on the optical bench.



Launch Stack Configuration

Inter-spacecraft Measurement Concept

The distance measurement is divided into three parts - a "long arm" interferometer which is the distance between the optical benches in the near and far spacecraft, and two "short arm" interferometers. The short arm interferometer is fully verified by ground testing for LISA Pathfinder, as well as flight tested. The short arm for LISA can also be fully verified on the ground. Long arm testing will require a unique approach.